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Mobile collaborative welding system for complex welding seams

Junze Yuan[a], Hongan Han[a,b], Yonggang Liu[a,b], Zhanxi Wang[a], Chen Zheng[a,c,*]

[a]*School of Mechanical Engineering, Northwestern Polytechnical University, 127 West Youyi Road, Xi'an Shaanxi, 710072, P. R. China*
[b]*Henan Weihua Heavy Machinery Co., Ltd, Weihua Road, Changyuan Henan, 453499, P. R. China*
[c]*CSSC Huangpu Wenchong Shipbuilding Company Limited, Guangzhou, 510715, P. R. China*

* Corresponding author. Tel.: +86-15102904023; fax: +86-29-88492261. *E-mail address:* chen.zheng@nwpu.edu.cn

Abstract

The growing variety of products brings various workpieces, which have complex welding seams that cannot be welded by current welding robots fixed in the welding stations or carried by the gantry. Therefore, this paper proposes a mobile collaborative welding system composed of an AGV (Automated Guided Vehicle) and a 6-DOF (Six-Degree-of-Freedom) collaborative robot. Considering the complex welding seams, a mobile collaborative welding method is proposed. The collaborative welding method includes three steps, i.e., welding seam acquisition, welding seam classification and segmentation, and welding task allocation. The authors present a new approach to acquire the spatial position characteristics of welding seams based on the human-machine collaboration. According to the spatial position characteristics of the welding seams, the welding type identification and classification segmentation can be obtained. Finally, the welding tasks of the robot and AGV can be allocated.

Keywords: Mobile welding system; welding seams acquisition; task allocation; collaborative robot

1. Introduction

Collaborative robots have been widely implemented in modern manufacturing for the purpose of collaborating with human workers in manufacturing, due to their capacity for safety and precision. Therefore, some manufacturing fields are beginning to use collaborative robots to work along with people. The flexibility and efficiency of collaborative robots in the welding domain have attracted increasing attention from both academia and industry. However, a growing variety of products brings various workpieces with complicated welding seams, which cannot be welded by current welding robots fixed in the welding stations. On the one hand, welding seams exceeding the reach of robots make it hard to complete welding at one time, which causes breakpoints in seams and influences welding quality. On the other hand, complex welding seams within the reach of robots may generate inappropriate welding torch posture in particular situations, which causes collisions of robots and poor welding quality.

The AGV, gantry, or other mobile platforms that improve the flexibility of robots have been integrated into the robotic welding system. The vast majority of mobile welding systems consist of gantries and welding robots. The use of gantries decreases the difficulty of long-distance welding seams beyond the reach of robots. However, there are still challenges for complex welding seams since the gantries expand the welding space linearly. By contrast, the AGV can almost extend robots' welding space to the entire workshop due to its high flexibility and small volume.

In this paper, the authors propose a mobile collaborative welding system composed of an AGV and a 6-DOF collaborative robot in order to achieve more efficient welding process and higher welding quality in complex welding seams. This mobile collaborative welding system can take advantage of the precision and capacity of the human-machine collaboration of the 6-DOF collaborative robot and the mobility of the AGV. Compared to the traditional fixed robotic welding stations and welding robots carried by gantries, the proposed mobile collaborative welding system can conveniently acquire the complex welding seams by dragging manipulator manually and effectively solve the difficulties in welding of complex welding seams applying classification and segmentation of welding seams & task allocation.

* Corresponding author

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The structure of this paper is organized as follows: Section 2 conducts a deep review on the current technology of welding robots and presents that current robotic welding systems are inapplicable to the welding seams with complex shape. Section 3 introduces the mobile collaborative welding system based on AGV. Section 4 draws the conclusion and points out the future research.

2. Literature review

Robotic welding systems have been widely applied in the welding domain. In current robotic welding system, the industiral robot always carries the welding torch, which is installed at the end of the robot, to complete the welding tasks. Recently, semi- and fully-automated robotic welding systems have been widely adopted by the welding domain [1]. In order to achieve a high-precision welding process, the first step is to extract the position information of the actual welding seams. Then, by using the position information obtained in previous step, the robotic welding system executes the task allocation step, which divides the welding task into subtasks according to the welding seam characteristics. Once the above two steps have been completed, the robotic welding system can carry out the welding process.

2.1. Welding seam acquisition

The acquisition of welding seams mainly depends on the extraction from the model of a workpiece and point cloud data obtained by three dimensional laser scanner. The model and the actual size of the workpiece are not always consistent, resulting in errors during welding. The vision sensors combined with laser can automatically extract the welding seam, which has better programming flexibility and welding precision. To achieve fast and accurate extraction of welding seam, laser structured light has been widely applied to welding robots [2]. Wu et al. propose a line extraction algorithm for seam tracking system based on the modified Hough algorithm, which has simple implementation and small computation but low precision of measurement [3]. Yang et al. design a grating projection system based on a digital light processing projector that can realize the extraction of the welding seams and off-line three dimensional path teaching [4]. This system is limited for a broader working view because of the grating projection sensor. Li et al. propose a new teaching system aiming to simplify the programming process by adding a path point generation module, which depends on a RGB-D sensor to obtain the point cloud and generate path points for space curve seam [5]. However, this teaching system has greater errors facing thin welding seams. Long et al. propose an improved self-adaptive extraction method based on the Steger method, which has high precision but costs large computation [6]. Li et al. reconstruct the welding seams by using the fringe pattern [7]. Muhammad et al. extract the geometric characteristics of welding seams by using laser light source and industrial camera [8]. Huang et al. introduce the HUST-SM vision system composed of a CCD camera and four structured laser light to give the integrated 2D and 3D visual data of welding seams [9]. In the acquisition of welding seams, there are deficiencies for the extraction from the model of workpiece and point cloud data gained by three dimensional laser scanner, which affect welding accuracy and quality.

2.2. Task allocation

In the manufacturing industry, production can be seen as multiple subtasks arranged in a certain order and can be allocated to different subsystems through task allocation. Costelha et al. introduce a framework of robot task planning using Petri Nets, including modeling, analysis, planning, and execution [10]. Zhang et al. propose a dynamic cloud task scheduling and task allocation method based on a two-stage strategy, which can plan and control discrete behavior and continuous behavior and express the interaction between the two behaviors [11]. Lehoux-Lebacque et al. establish the polynomial complexity of the coupled task allocation problem and the difference of task allocation process when the number of tasks changes is discussed [12]. The above task allocation methods will effect the welding efficiency of the welding system. A convenient and fast task allocation standard based on the welding seams' information is needed.

2.3. Mobile welding system

Traditionally, robotic welding systems are fixed in the welding stations, which are inability to weld huge and complex workpieces. The mobile platform, such as gantry and vehicle, can solve the problem by expanding the limited workspace of welding robots. Zhen et al. design a mobile welding system based on the gantry implemented in shipbuilding that applies a knowledge-based program generation approach, which can weld linear seams within the reachable range of the systems [13]. However, for welding seams beyond the working area or with complex shapes, the designed system cannot complete the welding well. Lv et al. propose a mobile welding robot based on seam position detection and tracking that can weld curved welding seams on the plane. But the mobile welding robot designed by Lv cannot weld the seams that change in the vertical direction [14]. Li et al. propose a mobile welding robot guided by seam tracking based on the fuzzy-gaussian neural network with high precision of seam track but cannot weld the seams on a different plane [15]. Dung et al. design a two-wheeled welding mobile robot for tracking curved welding seams, which is also focused on welding seams on the same plane [16]. Chung et al. proposed a mobile welding robot for seam tracking through a smooth curved joint path at a constant welding speed controlled by a nonliner controller [17]. In the welding of the huge and complex-shaped workpieces, the current wheeled and gantry mobile welding system cannot meet the high quality and efficiency welding since they cannot move to the appropriate posture for welding.

Above survey indicates that current robotic welding systems can complete the welding tasks for the linear and short welding seams well, but it is still a challenging task when facing

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the complex welding seams. In other words, the current robotic welding systems can only applied in the simple welding tasks and welding automation is negatively affected. In order to solve the problems in the acquisition of complex welding seams and welding path planning, the cooperative robots and AGV are introduced to overcome the shortcomings of the existing robotic welding systems. Next section discusses the working principle and main techniques of the proposed mobile collaborative welding system.

3. Mobile collaborative welding system

3.1. Working principle of mobile collaborative welding system

Welding robots were first applied to industrial manufacturing in the 1960s for efficiently welding. Traditional welding robots are fixed in the work stations or carried with gantries are not suited for complex welding seams. As a result, welding quality cannot be guaranteed that impedes the development of robotic welding technology. The mobile collaborative welding system introduces the AGV and collaborative robot. The AGV gives collaborative robot a broader workspace. The collaborative welding robot can efficiently locate to the position of complex welding seams by dragging the torch manually, which avoids error due to placement of workpiece. The framework of the proposed mobile collaborative welding system is represented in Fig. 1.

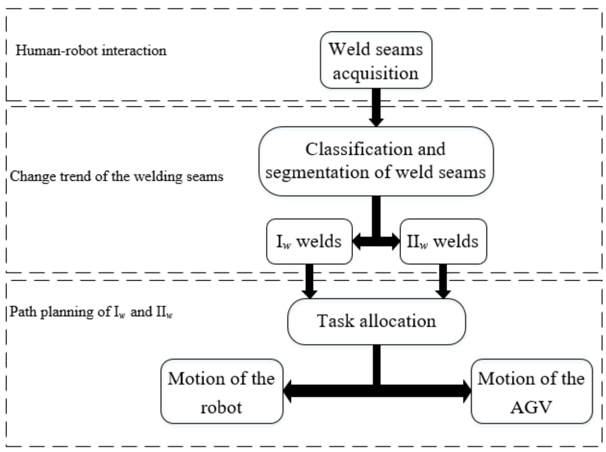

Fig. 1. Framework of the mobile collaborative welding system.

The design principle of the mobile collaborative welding system can be divided into three parts: (1) human-robot interaction in the acquisition of welding seams, (2) classification and segmentation of welding seams, (3) task allocation.

- Human-robot interaction in the acquisition of welding seams: the welding seams are acquired by human dragging the end-effector of collaborative robot along the welding seams, meanwhile the collaborative robot recording the positions of the end-effector. The positions will be used for classification and segmentation of welding seams.
- Classification and segmentation of welding seams: according to the positions of the welding seams in the world coordinate, the changing trend can be obtained, and the welding seams can be classified into two categories, I_w and II_w, which is the basis in the following task allocation.
- Task allocation: the mobile welding system is divided into two, the collaborative robot subsystem and the mobile subsystem. Through the analysis of the characteristics of the subsystems and the characteristics of different types of welding seams, the task allocation is carried out to complete the path planning of the robot and the AGV.

With the introduction of the AGV and collaborative robot, the welding range has been extended. Applying the mobile collaborative welding system in the manufacture can provide operators with a new welding method for complex welding seams.

3.2. Main techniques of mobile collaborative welding system

First, the AGV should be close to the workpiece and establish the world coordinate to define the position of the welding seam. Second, operator should drag the end-effector of the robot to the start of the welding seam while the robot is recording the positions of the end-effector at a fixed frequency and saving the positions in the base coordinate of the robot, which can form a set of points to represent the welding seam. Thirdly, the process of classification and segmentation of welding seams will divide the positions of the welding seam into two categories. The first category is planar welds, and the second category is spatial welds. Then, the motion of the system will be divided into different blocks for different segments of the welding seam.

3.2.1. Human-robot interaction in the acquisition of welding seams

The collaborative robot has the advantage that can work alongside the operator, which can be used in the acquisition of welding seams. At first, operator should drag the end-effector of the robot to the start of the welding seam and make sure that the end of the torch touches the workpiece. It is supposed that the robot is installed at the center of the AGV to ensure that the base coordinate of the robot overlaps the geometric center of the AGV. After the establishment of the world coordinate, operator should pull the end of the torch along the welding seam while the collaborative robot records the positions of the end-effector. The coordinate of the AGV is shown as follows:

$$P_a = \{x_a, y_a, \theta_a\}^{\mathrm{T}} \tag{1}$$

where x_a and y_a are the position of the AGV in the plane and θ_a is the angle between AGV head pointing and the x-axis positive half of the world coordinate. The coordinate of the end of the end-effector is shown as follows:

$$P_t = \{x_t, y_t, z_t\}^{\mathrm{T}} \tag{2}$$

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Hence, the coordinate of the i^{th} point, P_i, in the world coordinate is represented by the coordinate of the AGV, P_a, and the coordinate of the end-effector, P_t which is shown as follows:

$$P_i = \begin{bmatrix} \cos\theta_a & -\sin\theta_a & 0 & x_a \\ \sin\theta_a & \cos\theta_a & 0 & y_a \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot P_{ti} \tag{3}$$

where P_{ti} is the coordinate of the i^{th} position of the end-effector in the base coordinate. The shape of the welding seam can be expressed as a set of these points:

$$W = \{P_1, P_2, \cdots, P_n\} \tag{4}$$

However, during the acquisition of the welding seams, the operator cannot make the end-effector of the robot coincide with the welding seams all the time, resulting in some deflected points in the W. It is necessary to filter the point set to get accurate welding seams. The deflected points are caused by the operator, which means that the points adjacent to the deflected ones are on the welding seams. To select out the deflected points, the angles between the vectors of the adjacent points are calculated, which have greater changes near the deflected points than those near points on the welding seams shown in Fig. 2. With the filtered point set, a curve of the welding seams can be fitted and the classification and segmentation of welding seams can be carried out.

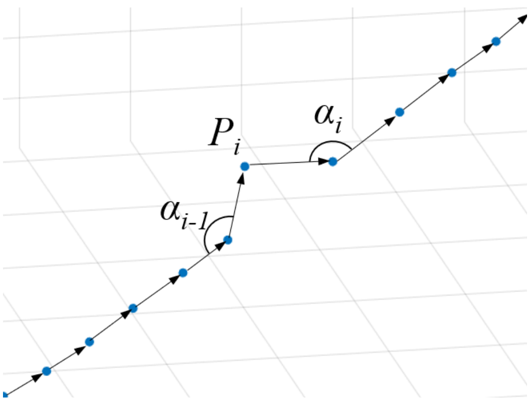

Fig. 2. The process of task allocation.

3.2.2. *Classification and segmentation of welding seams*

It is difficult to discuss the path planning of the system for the welding seams fitted into a spatial curve. To carry out the path planning of the system, it is necessary to analyse the geometric characteristics of the welding seams and classify them. This paper designs a new way to classify the welding seams into different types and segments according to the gradient in the z-direction. The welding seams that are parallel to the ground plane is defined as type I_w. On the contrary, the welding seams with changes in the vertical direction are defined as type II_w. The trend changes in the vertical direction can be described by the gradient mentioned in the follows:

$$\mathrm{z} = \begin{bmatrix} z_x \\ z_x \end{bmatrix} = \begin{bmatrix} \frac{\partial z}{\partial x} \\ \frac{\partial z}{\partial y} \end{bmatrix} \tag{5}$$

The length of the gradient z is expressed as:

$$\begin{cases} |\nabla \mathrm{z}| = \sqrt{{z_x}^2 + {z_x}^2} \leq r_{thres}, \mathrm{I}_w \\ |\nabla \mathrm{z}| = \sqrt{{z_x}^2 + {z_x}^2} > r_{thres}, \mathrm{II}_w \end{cases} \tag{6}$$

where r_{thres} is the classification threshold in the z-direction. It is classified as type II_w when the gradient is greater than r_{thres}, otherwise as type I_w. Classification and segmentation of welding seams effectively reduces the complexity of the welding seams by dividing the complex spatial curve into two types which will be discussed in the task allocation.

3.2.3. *Task allocation*

The mobile welding system can be divided into the mobile subsystem and the collaborative robot subsystem. The mobile subsystem can move in the plane while the collaborative robot subsystem can move in the vertical direction. Hence, the path planning of the mobile welding system is composed of the path planning of two subsystems. The process of task allocation is shown in Fig. 3. The I_w welding seams is welded by the AGV' motion because it is parallel to the ground. Firstly, it is necessary to plan the path of the AGV. To minimize the error caused by the motion of the AGV, the path of AGV needs to be parallel to the welding seams as shown in Fig. 4.

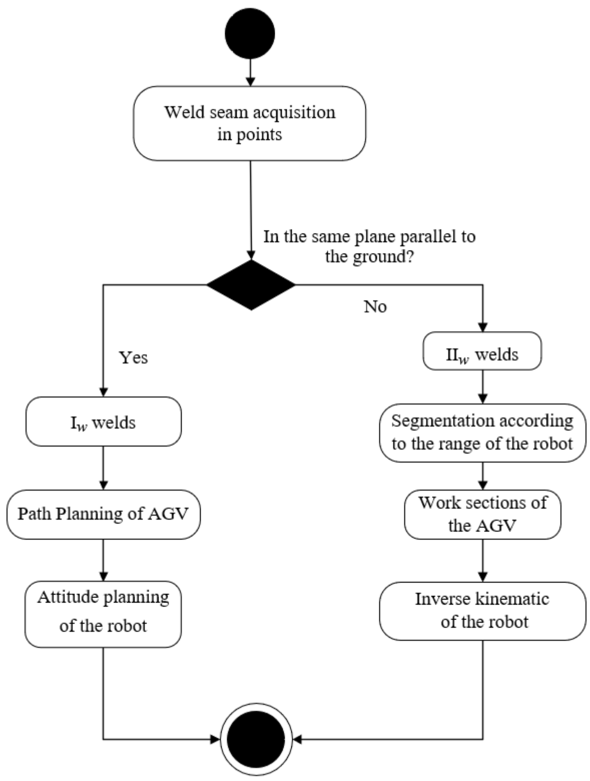

Fig. 3. The process of task allocation.

After the path planning of the AGV, according to the expected poseture of the torch, the inverse solution of the robot is obtained, which contains the rotation angles of each joint of the robot. As the AGV forward direction is always on the tangent

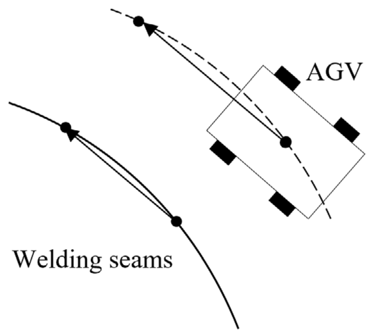

Fig. 4. Path planning of the AGV.

of the welding point, it can ensure that the posture of the torch is always in the best posture to the welding seams.

The II_w welding seams requires the collaboration of the AGV and collaborative robot. First, it is necessary to calculate the workspace of the robot on the AGV. As shown in the Fig. 5, the II_w welding seams can be divided into different sections and each section have a work position for the AGV according to the working range of the robot and the safe distance l between the AGV and the workpiece. For the welding seams in sections, the

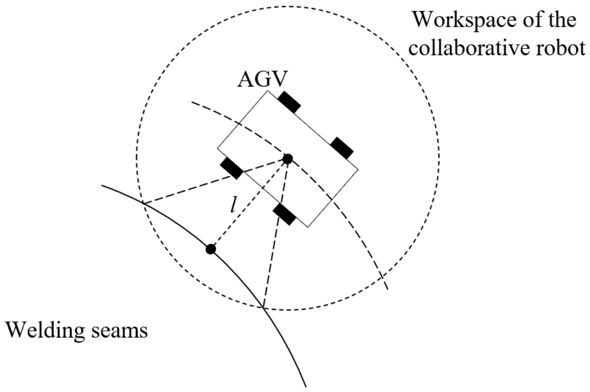

Fig. 5. Sections of the welding seams.

rotation angles of each joint of the robot can be solved out by inverse kinematics (ik), as shown in follows:

$$\begin{cases} P_{iII} = \begin{bmatrix} \cos\theta_a & -\sin\theta_a & 0 & x_a \\ \sin\theta_a & \cos\theta_a & 0 & y_a \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot P_i \\ \theta_{II} = ik(P_{iII}, a, b, c) \end{cases} \tag{7}$$

where a, b and c are the rotation angles of the end-effector. The inverse kinematics solutions of the robot are not unique that will be up to eight groups. In order to ensure the smooth movement of the robot, the robot selects a group with the smallest joint changes in multiple sets of inverse solutions. The selection standard is shown in Fig. 6. The variation of the first joint (J_1) of the robot has the maximum influence on the position of the end-effector and the other joints' influence decreases in turn. Therefore, the variation of J_1 relative to the previous position is calculated at first. The solutions with minimum variation are retained for the variation of the next joint until only one solution is left. By the inverse kinematics of the welding seams in the section, the path planning of the collaboration robot can be obtained and the welding can be carried out. The AGV will move to the next work position after the welding is finished.

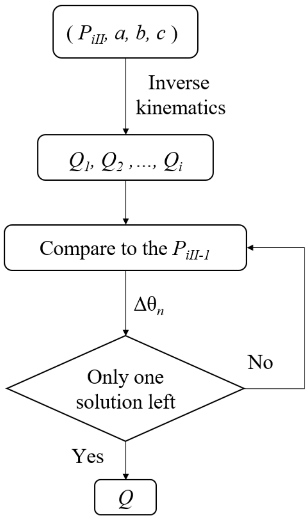

Fig. 6. Selection the inverse kinematics solution.

Different from the path planning of the whole welding system, task allocation separates the welding paths planning of different types of welding seams, which simplifies the complexity of the welding seams. The I_w and II_w welding seams apply different modes to utilize the characteristics of the AGV subsystem and the collaborative robot subsystem to obtain high efficiency and higher welding quality.

4. Discussion and conclusion

This paper proposes a mobile collaborative welding system composed of an AGV and a 6-DOF collaborative robot to achieve the efficient and high-quality welding process for complex welding seams. The collaborative welding process includes three steps, i.e., welding seam acquisition, welding seam classification and segmentation, and welding task allocation. First, the authors present a new welding seam acquisition approach based on human-machine collaboration. According to the spatial position characteristics of the welding seams, the welding type classification and segmentation are discussed. Finally, the welding tasks of the robot and AGV are assigned. The future research can be divided into two parts. On the one hand, more attention should be paid to the experimental platform which can validate the feasibility of the proposed method. On the other hand, machine vision and other sensors should be integrated into the mobile collaborative robotic welding system, so that the welding accuracy of the mobile welding system can be improved.

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